

**Contract # N00014-14-C-0020**

**Pilot-in-the-Loop CFD Method Development**

**Progress Report (CDRL A001)**

**Progress Report for Period: January 21, 2016 to April 20, 2016**

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## **Section I: Project Summary**

### **1. Overview of Project**

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) virtual dynamic interface (VDI) research topic area “Fast, high-fidelity physics-based simulation of coupled aerodynamics of moving ship and maneuvering rotorcraft”. The work is a collaborative effort between Penn State, NAVAIR, and Combustion Research and Flow Technology (CRAFT Tech). This document presents progress at Penn State University.

All software supporting piloted simulations must run at real time speeds or faster. This requirement drives the number of equations that can be solved and in turn the fidelity of supporting physics based models. For real-time aircraft simulations, all aerodynamic related information for both the aircraft and the environment are incorporated into the simulation by way of lookup tables. This approach decouples the aerodynamics of the aircraft from the rest of its external environment. For example, ship airwake are calculated using CFD solutions without the presence of the helicopter main rotor. The gusts from the turbulent ship airwake are then re-played into the aircraft aerodynamic model via look-up tables. For up and away simulations, this approach works well. However, when an aircraft is flying very close to another body (i.e. a ship superstructure) significant aerodynamic coupling can exist. The main rotor of the helicopter distorts the flow around the ship possibly resulting significant differences in the disturbance on the helicopter. In such cases it is necessary to perform simultaneous calculations of both the Navier-Stokes equations and the aircraft equations of motion in order to achieve a high level of fidelity. This project will explore novel numerical modeling and computer hardware approaches with the goal of real time, fully coupled CFD for virtual dynamic interface modeling & simulation.

Penn State is supporting the project through integration of their GENHEL-PSU simulation model of a utility helicopter with CRAFT Tech’s flow solvers. Penn State will provide their piloted simulation facility (the VLRCOE rotorcraft simulator) for preliminary demonstrations of pilot-in-the-loop simulations. Finally, Penn State will provide support for a final demonstration of the methods on the NAVAIR Manned Flight Simulator.

#### **Activities this period**

During this reporting period, PSU continued to collaborate with CRAFT-Tech to improve the efficiency of the new coupling interface. We have demonstrated our first real-time pilot-in-the-loop simulation for a simplified CFD wake case, as well as a near-real-time/real-time batch simulations with a pilot model and a coarse and fine computational grid, respectively. These simulations were run with the MPMD-MPI communication protocol and using the CRAFT structured flow solver.

#### **Demonstrations of Real-time Fully Coupled Simulations**

Several efforts have been conducted towards the real-time Pilot-in-the-loop (PIL) CFD simulations. All these efforts have been performed on CRAFT Tech’s in-house cluster with 32 nodes, each containing 8 Intel Xeon E5530 processors (2.4 GHz), using a 40Gbps Infiniband interconnect. (32 nodes x 8 procs = 256 processors)

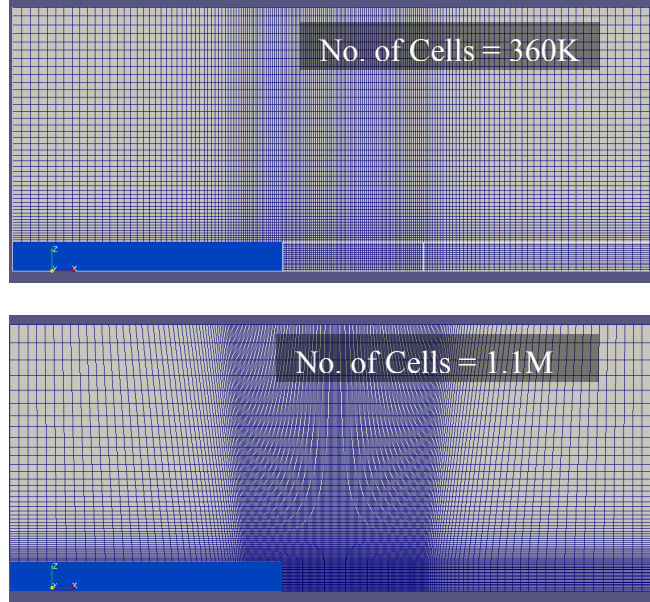
**Table 1 – Description of simulated cases**

<b>Case #</b>	<b>Piloted / Non-piloted?</b>	<b>Flow Assumption</b>	<b>Grid Size</b>
Case 1	Non-piloted	Viscous flow	1.2 million
Case 2	Non-piloted	Inviscid flow	380k
Case 3	Piloted	Inviscid flow	380k

Table 1 shows the properties of the simulation cases performed. A set of three simple shedding small backstep cases were performed using two relatively small computational domains: 1) a finer grid with 1.2 million cells, and 2) a coarser grid with 360k cells. Figure 1 shows the comparisons of the grid resolutions used in the demonstration cases. The minimum cell size in the refined region downstream of the backstep was 1ft and 4ft for Case 1 and Case 2, respectively.

#### **Case I: Non-real-time Baseline Coupled Simulation**

The first case was chosen as a “baseline” case, which was expected to generate a better-resolved shedding wake. The structured CRAFT CFD solver was used with viscous flux term is included and a wall function boundary applied to the backstep surfaces. A relatively small computational domain with 1.2 million cells was used in the simulation. Using the NLDI controller, the helicopter executed a landing trajectory within a simulation period of 60 seconds. The GENHEL-PSU time step was 0.01 seconds and the CFD time step was 0.005 seconds, which took 0.075 seconds per iteration to run on 256 processors (15 times slower than real-time). GENHEL-PSU was set to run one time step and CFD solver was set to run two time steps in between the data exchanges. The dimensions of the backstep (width = 60 ft) produce shedding characteristics similar to a ship flight deck for this case.



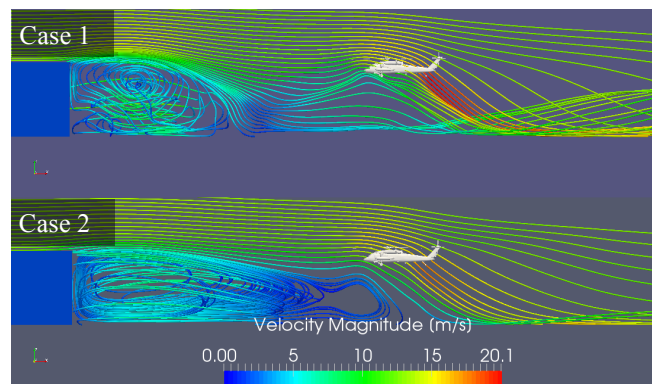
**Figure 1. Comparison of grid resolutions of the computational domains used in the demonstration cases.**

#### **Case II: Real-time Coupled Simulation**

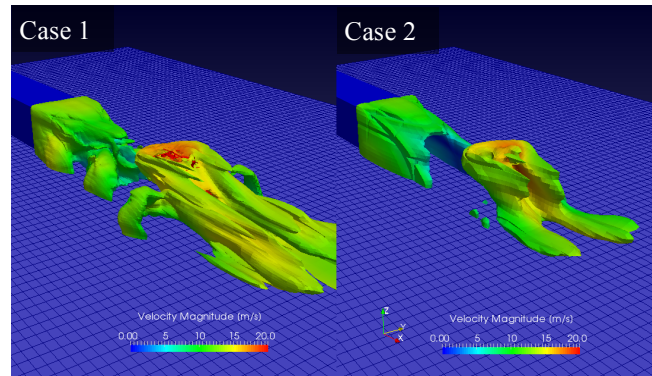
Using the CRAFT CFD structured solver running with 5th-order upwind Roe/TVD scheme without viscous flux terms on a structured grid (380k cells), a real-time coupled simulation was achieved. The same NLDI controller was used to fly the helicopter on the same landing trajectory; in order to compare the results with the more resolved wake solution of Case I. In this case, using coarser mesh structure and

inviscid flow assumption allowed us to use a bigger time step in the CFD calculations. The CFD time step was 0.02 seconds and GENHEL-PSU exchanged data with CRAFT CFD every 2 steps. The CFD calculations took about 0.019 seconds per iteration to run a time step of 0.02 seconds, resulting in real-time execution speeds. The shedding characteristics were not as well resolved as the non-real-time CFD case (Case 1) because of the inviscid flow assumption and the coarser grid resolution.

Figure 2 shows a comparison of the streamline distributions between Case 1 and Case 2. In Case 1, the recirculation region behind the backstep is narrower compared to Case 2. The streamline distribution is more laminar compared to Case 1. Figure 3 shows the vorticity distribution of Case 1 and Case 2 at the same simulation time indicating the more resolved shedding flowfield of the backstep wake and the less dissipative rotor tip wake of Case 1 due to the finer grid resolution. The inviscid flow assumption and the coarser grid resolution of Case 2 results in relatively poor shedding characteristics compared to Case 1. However, these simplifications were required to achieve the real-time execution speeds needed for a demonstration of the pilot-in-the-loop simulation framework on available computing hardware.



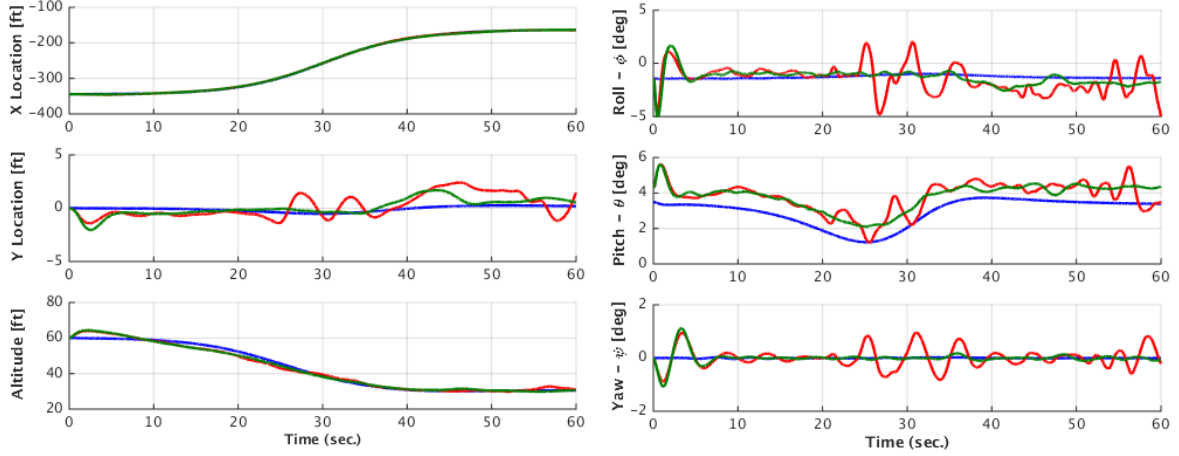
**Figure 2. Streamline distributions for Case 1 and Case 2.**



**Figure 3. Vorticity distribution for Case 1 and Case 2.**

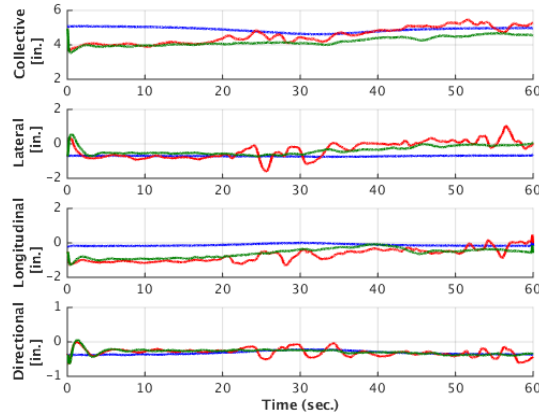
Figure 4 shows the dynamic response of the helicopter as it executes the landing maneuver in the simulated cases. As mentioned before, the NLDI autopilot controller holds the helicopter at the desired trajectory. In the “No-coupling” case, GENHEL-PSU uses the Pitt-Peters inflow model to calculate the rotor downwash and there is no airwake disturbance to the helicopter. However, on Case 1 and Case 2, the GENHEL-PSU code is fully coupled with the CFD solver and the Pitt-Peters inflow model is replaced with the CFD-calculated flowfield solution. As shown in Figure 4a, the controller successfully holds the position of the helicopter on the desired trajectory. The helicopter drifts more in Case 1 compared to the other two cases. A similar behavior can also be seen on the attitude response of the helicopter. There are

many fluctuations on the roll and pitch dynamics of the helicopter in Case 1. We see a smoother flight on ‘Case 2’ and ‘No Coupling’ cases. This is a result of inviscid flow assumption and the less resolved, more dissipative grid, which suppresses the turbulent behavior of the flow. Additionally, the helicopter trims at slightly higher collective input on Case 1 when it gets close to the ground, since the ground effect is modeled more precisely in this case.



a) Positions

b) Attitudes



c) Autopilot Commands

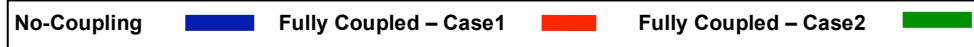
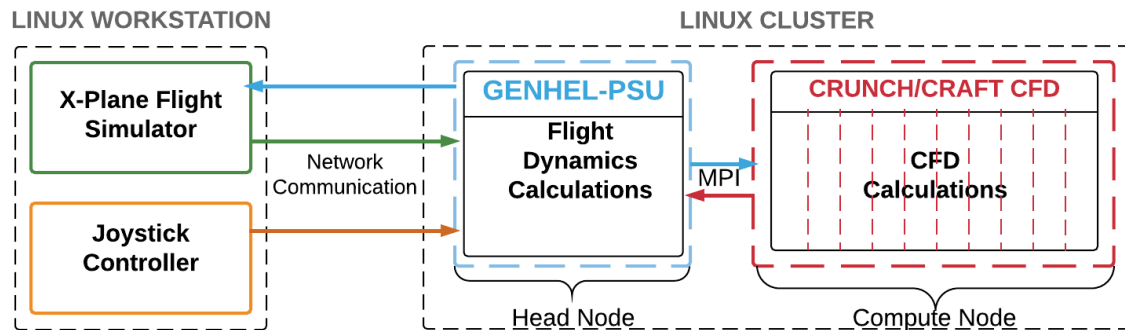


Figure 4. Variations in dynamics of the simulated helicopter approaching to the small backstep.

### Case III: Real-time Pilot-in-the-Loop CFD Simulation

For the Pilot-in-the-Loop CFD (PILCFD) demonstration cases, a network configuration on a CRAFT Tech Linux cluster was developed as shown in Figure 5. The helicopter flight dynamics simulation (GENHEL-PSU) was run on the head node of the cluster, which enabled network communication ports outside the cluster network to a Linux workstation running the joystick controller (for pilot inputs) and X-Plane (Figure 6) graphics to display the simulation. The CRAFT CFD solver was run in parallel over all 32 compute nodes (256 processors) on the cluster using a 40Gbps Infiniband interconnect.

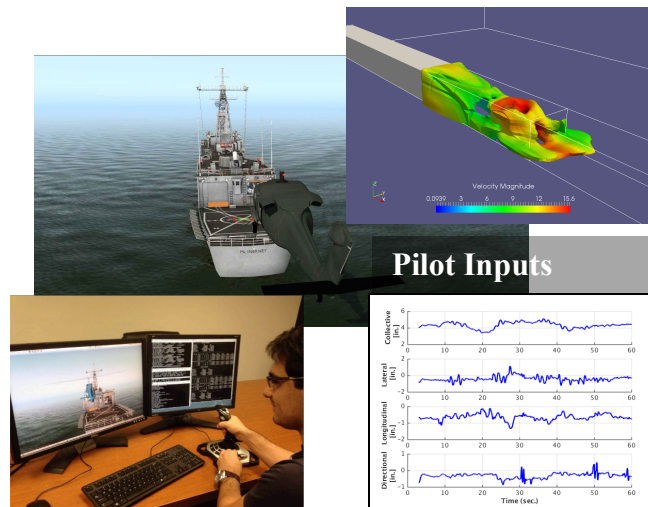


**Figure 5. PILCFD demonstration case network configuration.**

Using the same grid as in Case 2 (380k), with a person flying the helicopter in the wake, a real-time piloted simulation (Figure 7) was performed. The CFD calculations (flow calculations + MPI data exchange) took about 0.02s to run a time step of 0.02 seconds. Therefore GENHEL (0.01s time step) exchanged data with the CFD every 2 steps. The joystick controller was set to 0.025s update interval which gave a smooth response of the flight dynamics with the simulation. It was found that this interval must be slightly greater or equal to the physical wall time required to complete one CFD solver time step plus the time required to complete rest of the operations (time required to complete two GENHEL time step + time required to complete all the data transfer over the network + network latency). This update interval produced a smooth flight simulation with the dynamics and CFD working in "real-time" execution speeds.



**Figure 6 – A representative frigate ship and UH-60 helicopter model used for the PILCFD demonstrations.**



**Figure 7 – Real-time PILCFD demonstration case.**

The same simulation case was repeated with CRAFT CFD writing the solution data to disk during the simulation. This operation significantly slowed the simulation down (it took 0.045sec to run a time step of 0.02 seconds) but enabled us to generate the CFD data that is synched to the X-Plane graphics animation as well as the flight dynamics data from GENHEL-PSU. The joystick was set to a 0.05s update interval, which produced a smooth flight simulation with the dynamics and CFD working in “slow motion”, about 2.5 times slower than the real-time. The obtained CFD solution was not as accurate as Case1 on this coarser grid, however it successfully demonstrated the simulation framework with flow calculations based on the pilot’s inputs to steer the helicopter.

The timings achieved on all three cases are listed on Table 2. On the last two cases (Case 2 and 3), “real-time” execution speeds were achieved.

**Table 2. Timings achieved on the performed simulation cases.**

	<b>CFD time step [s]</b>	<b>Required wall time for CFD time step [s]</b>	<b># of CFD steps between data exchange with GENHEL</b>
<b>Case 1</b>	0.005	0.075	2
<b>Case 2</b>	0.02	0.019	1
<b>Case 3</b>	0.02	0.02	1

## 2. Significance of Results

A set of simulations was conducted to investigate the first steps towards the practical real-time virtual dynamics interface simulations. Improvements to the coupling interface are presented that, for a simplified shedding wake example, we are able to achieve real-time execution speeds for the fully coupled simulation on a Linux cluster utilizing 256 processor cores. A demonstration of our first Pilot-in-the-Loop CFD (PILCFD) simulation for this simplified CFD wake case was performed and results of the simulation were presented.

Currently, a pilot-in-the-loop CFD simulation framework was demonstrated for a simplified CFD wake case to establish the coupling interface between the helicopter flight dynamics and the CFD solver within a real-time simulation environment. In this demonstration, in order for the CFD solver to perform at real-time execution speeds on an available Linux cluster, the CFD case was run on a small (~300K cells) grid. The small grid sized limited the geometry of the wake generating structure to a simplified 3D backstep. Additionally, as shown by the comparisons of Case 1 and Case 2 results, significant wake shedding physics were not resolved due to the coarse grid and inviscid assumption that were required to reduce the computational cost of the solver for the demonstration.

## 3. Plans and upcoming events for next reporting period

- We will continue to collaborate with CRAFT Tech to improve the efficiency of the coupling interface. To achieve a practical PILCFD simulation framework that can be used in piloted virtual dynamic interface flight simulation, future efforts will be focused on improving the performance of the CFD computations so that a ship airwake model on the order of 5-10 million grid cells (similar to grid sizes of airwake datasets currently employed in dynamic interface CFD simulations) can be included in the fully coupled simulation framework. This will require significant speed up of the CFD solver and will



necessitate hardware solutions such as the application of GPU technology and ongoing efforts to apply the latest HPC architecture to increase performance.

- Efforts towards implementing the tail rotor as an actuator disk in the CFD domain are still ongoing and we are expecting to finalize this implementation before the next quarter. Results will be presented on the next quarterly progress report.
- There is an ongoing effort towards developing efficient methods to visualize the CFD flow field during the piloted simulation will be beneficial to provide feedback of airwake dynamics to the pilot.

#### **4. References**

None.

#### **5. Transitions/Impact**

No major transition activities during the reporting period.

#### **6. Collaborations**

We had a meeting with CRAFT Tech in late February 2016 to work towards the real-time demonstrations of fully coupled simulations. CRAFT Tech in house cluster were used to run the simulations and results were presented in this report and will be presented in the next AHS Forum in May 2016, as well.

The work continues to involve close collaboration between PSU, CRAFT-Tech, and NAVAIR.

#### **7. Personnel supported**

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

#### **8. Publications**

Oruc, I., Shenoy, R., Shipman, J., and Horn, J.F., "Toward Real-time Fully Coupled Flight Simulations of the Helicopter/Ship Dynamic Interface," American Helicopter Society Forum 72, West Palm Beach, FL, May 2016. (*will be presented in the Modeling and Simulations session on May 17<sup>th</sup>, 2016.*)

Oruc, I., Horn, J.F., Shipman, J., and Shenoy, R., "Coupled Flight Dynamics and CFD Simulations of the Rotorcraft/Terrain Interactions," AIAA Modeling and Simulation Technologies Conference, AIAA SciTech, San Diego, CA, January 2016.

Oruc, I., Horn, J.F., Polsky, S., Shipman, J. and Erwin, J., "Coupled Flight Dynamics and CFD Simulations of the Helicopter/Ship Dynamic Interface", American Helicopter Society Forum 71, Virginia Beach, VA, May 2015.

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